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Effects of urban and non-urban land cover on nitrogen and phosphorus runoff to Chesapeake Bay

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ABSTRACT

The aim of this study was to determine the effects of catchment and riparian stream buffer-wide urban and non-urban land cover/land use (LC/LU) on total nitrogen (TN) and total phosphorus (TP) runoff to the Chesapeake Bay. The effects of the composition and configuration of LC/LU patches were explored in particular. A hybrid-statistical-process model, the SPAtially Referenced Regression On Watershed attributes (SPARROW), was calibrated with year 1997 watershed-wide, average annual TN and TP discharges to Chesapeake Bay. Two variables were predicted: (1) yield per unit watershed area and (2) mass delivered to the upper estuary. The 166,534 km^2 watershed was divided into 2339 catchments averaging 71 km^2. LC/LU was described using 16 classes applied to both the catchments and also to riparian stream buffers alone. Seven distinct landscape metrics were evaluated. In all, 167 (TN) and 168 (TP) LC/LU class metric combinations were tested in each model calibration run. Runs were made with LC/LU in six fixed riparian buffer widths (31, 62, 125, 250, 500, and 1000 meters (m)) and entire catchments. The significance of the non-point source type (land cover, manure and fertilizer application, and atmospheric deposition) and factors affecting land-to-water delivery (physiographic province and natural or artificial land surfaces) was assessed. The model with a 31 m riparian stream buffer width accounted for the highest variance of mean annual TN (r^2 = 0.9366) and TP (r^2 = 0.7503) yield (mass for a specified time normalized by drainage area). TN and TP loadings (mass for a specified time) entering the Chesapeake Bay were estimated to be 1.449×10^8 and 5.367×10^6 kg/yr, respectively. Five of the 167 TN and three of the 168 TP landscape metrics were shown to be significant (p-value ≤ 0.05) either for non-point sources or land-to-water delivery variables. This is the first demonstration of the significance of riparian LC/LU and landscape metrics on water quality simulation in a watershed as large as the Chesapeake Bay. Land cover metrics can therefore be expected to improve the precision of estimated TN and TP annual loadings to the Chesapeake Bay and may also suggest changes in land management that may be beneficial in control of nutrient runoff to the Chesapeake Bay and similar watersheds elsewhere.

1. Introduction

Land cover and land use (LC/LU) and its changes have large effects on water quality of streams, rivers, lakes, and estuaries. Urbanization is a pervasive form of LC/LU alteration that is rapidly growing (Paul and Meyer, 2001). This involves conversion of croplands, forests, grasslands, pastures, wetlands, and other cover types to residential and transportation and also commercial and industrial uses, thereby increasing the areas of impervious surfaces (Tsegaye et al., 2006). Impervious surfaces are quantifiable indicators that correlate very closely with increases in non-point (diffuse) sources of polluted runoff which degrades the quality of aquatic resources (Arnold and Gibbons, 1996). When combined with other anthropogenic and natural processes, landscape variables affect non-point nitrogen (N) and phosphorus (P) transport from land to the receiving water bodies and can contribute to eutrophication (nutrient enrichment) leading to poor water quality. Thus, LC/LU are critical properties that affect waterway pollution.

One such region where LC/LU changes are said to have affected regional water quality is the Chesapeake Bay watershed (Fig. 1a). The Chesapeake Bay is the largest estuary in the United States (US); its watershed (166,534 km^2) encompasses portions of six states: New York (NY), Pennsylvania (PA), Delaware (DE), Maryland (MD), West Virginia (WV), and Virginia (VA) and the District of Columbia (DC). Once considered a natural treasure due to its rich wildlife habitat and seafood industries, the Bay has been in steady decline starting with the colonial landscape transformations in the mid-1600s. By the 1990s, the human population of the watershed was approximately 16 million (McConnell, 1995), concentrated in fast-growing urban corridors (Fig. 1b). With the increase in population

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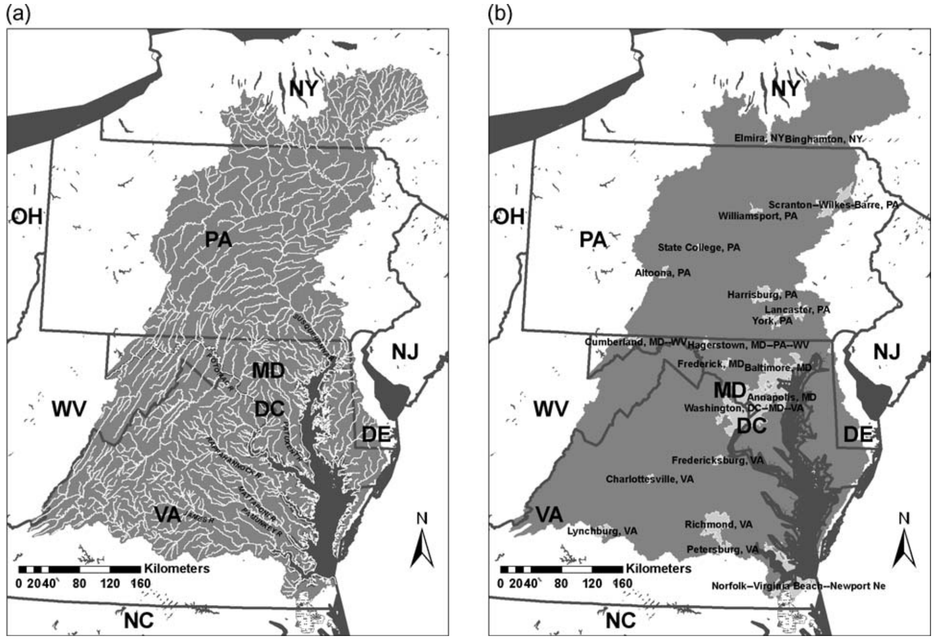

Fig. 1. The Chesapeake Bay watershed showing the locations of: (a) streams and rivers draining the estuary and (b) urban centers located within its boundaries.

and the built environment, LC/LU modifications within the watershed have contributed to sedimentation, turbidity, eutrophication, and hypoxia, consequently reducing submerged aquatic vegetation (SAV) and affecting many other aspects of the aquatic ecosystem (Breitburg, 1992; Hassett et al., 2005). As stricter regulations involving point source discharges, fertilizer and manure applications, and fossil fuel emissions that lead to atmospheric deposition are enacted, spatial information on how landscape properties affect regional nutrient runoff is needed to meet reduction goals.

Remotely sensed LC/LU data have recently become available for landscape analysis of the Chesapeake Bay watershed, including the Regional Earth Science Application Center's (RESAC) LC/LU, percent impervious surface area (% ISA), and percent tree cover (% TC) maps for 2000 (Goetz et al., 2003, 2004a,b; Jantz et al., 2005). Other remotely sensed datasets include the National Land Cover Dataset (NLCD) developed by the Multi-Resolution Land Characteristics (MRLC) (Homer et al., 2004) consortium for 1992 and 2001 which cover the entire conterminous United States. In particular, watershed-wide % ISA may yield important new information in linking the effects of urbanized areas to the estuary's water quality to compliment previous findings, within the watershed's smaller tributaries, correlating ISA to changes in stream hydrology (Carlson and Arthur, 2000; Jennings and Jarnagin, 2002; Dougherty et al., 2004).

Water quality models, such as the Hydrologic Simulation Program-FORTRAN (HSPF) (Bicknell et al., 1996, 2001) and the SPAtially Referenced Regressions On Watershed attributes (SPARROW) (Smith et al., 1997), have been applied to the Chesapeake Bay watershed (Preston and Brakebill, 1999; Linker et al., 2000; Brakebill et al., 2001; Brakebill and Preston, 2004; Goetz et al., 2004a). The HSPF model has often been used by management and regulatory entities, such as the Chesapeake Bay Program (CBP) and the United States Environmental Protection Agency (USEPA). HSPF is a process-based deterministic model that simulates nutrient loadings (mass) to the tidal tributaries (Linker et al., 2000). Complex process models of this type, however, require extensive temporal-dependent data (such as hourly rainfall, temperature, wind, and evapotranspiration) and detailed calibration. These requirements, generally limit application to a few watersheds (Alexander et al., 2002a).

The SPARROW model developed by the United States Geological Survey (USGS) has been used to estimate stream export and improve interpretability of model parameters (Alexander et al., 2002a). SPARROW utilizes a hybrid-statistical-process structure that implements deterministic functions with spatially distributed components, thus accounting for the dendritic features of watersheds (Alexander et al., 2002b). The model addresses many shortcomings of purely statistical or regression-based models by incorporating deterministic components of nutrient transport that includes flow paths, first-order loss functions, and mass-balance constraints (Alexander et al., 2002b). Furthermore, unlike HSPF, SPARROW provides robust measures of uncertainty. SPARROW was designed to reduce problems associated with data interpretation caused by sparse stream sampling measurement networks, network sampling biases, and basin heterogeneity. SPARROW has been applied at national (Smith et al., 1997, 2003; Alexander et al., 2004), regional (Alexander et al., 2000; Moore et al., 2004), and even localized watershed scales (Alexander et al., 2002a,b; McMahon et al., 2003).

Previous versions of SPARROW for the Chesapeake Bay watershed (Preston and Brakebill, 1999; Brakebill et al., 2001; Brakebill and Preston, 2004) have found no correlation between LC/LU and land-to-water delivery of non-point N and P. In these versions, however, LC/LU types were represented only as total areas of each cover type and did not take into account their spatial *configurations*, nor the possibility of differences in the role of LC/LU types in the riparian zones alone. Developed urban land cover in riparian zones have been shown to increase non-point N losses to streams (Groffman et al., 2002), unlike non-developed (forested) zones (Goetz et al., 2003).

Previous research has found that landscape metrics applied in catchment nutrient export models can improve nutrient predictions over those that use total LC/LU areal extent (Carle et al., 2005). Landscape metrics describe the spatial structure of patches, the cover classes of patches, and patch mosaics, and provide other measures of composition and configuration (Leitao et al., 2006). Landscape composition is the variety and abundance of patch types without regard to their spatial character or arrangement, whereas configuration quantifies spatial character and arrangement, position, and orientation of landscape elements. Although landscape metrics have been shown to improve correlations between the land surface and nutrient loading dynamics at catchment and riparian scales in subwatersheds of the Chesapeake Bay (Jones et al., 2001; King et al., 2005; Baker et al., 2006), there has not been a comprehensive analysis of the entire watershed.

Thus, the overall purpose of this study was to use the SPARROW model with improved LC/LU maps from remotely sensed data to determine the effects of LC/LU on TN and TP runoff from entire catchments and from the riparian stream buffer alone. Furthermore, the effects of landscape composition and configuration on runoff were explored.

2. Materials and methods

2.1. Chesapeake Bay watershed land cover and land use data

Three RESAC maps of LC/LU of the entire watershed were used, all at 30 m resolution. The first map had 18 distinct LC/LU types (Goetz et al., 2004a,b; Jantz et al., 2005); the second depicted % ISA (Goetz et al., 2004a,b; Jantz et al., 2005); the third was of % TC (Goetz et al., 2003, 2004a).

The watershed-wide % ISA map was partitioned into urban (≥10% ISA, class 1) and non-urban (<10% ISA, class 2). Non-urban areas were coded as the appropriate LC/LU class. Twelve LC/LU classes were used: urban/residential/recreational grasses; extractive land; barren land; deciduous forest; evergreen forest; mixed (deciduous-evergreen) forest; pasture/hay; cropland; natural grass; deciduous wooded wetland; evergreen wooded wetland; emergent (sedge-herb) wetland. The four built classes (low, medium, and high intensity developed, and transportation) were included in the urban grouping. The two remaining non-urban RESAC LC/LU classes: open water (not applicable) and mixed wetland (negligible areal coverage) were omitted. The % TC map was partitioned into non-forested (≤50% TC) and forested (>50% TC) classes. Overall, a total of 16 classes were created (Table 1).

2.2. Landscape metrics

Seven landscape metrics, previously shown to be significant indicators of downstream water impairment in catchments within the northeastern United States (Leitao et al., 2006), were used. These seven landscape metrics were calculated and applied to the 16 LC/LU classes. Five metrics (1–3, 6, and 7) measure landscape configuration and two (4 and 5) composition. The complete definitions for all seven metrics are given in Leitao et al. (2006).

(1) *Contagion* quantifies the degree to which LC/LU types were clumped as opposed to dispersed in many smaller fragments.
(2) *Area-weighted mean radius of gyration* (distance) measures connectivity by correlation length. Correlation length is the average distance one might traverse across a map from a random starting point and moving in a random direction while remaining in the same LC/LU (Keitt et al., 1997). Larger values of area-weighted mean radius of gyration indicate more connected landscapes.
(3) *Patch number* measures total LC/LU fragmentation by the total number of patches of a particular LC/LU.
(4) *Percentage of the landscape* area composed of a specified LC/LU.
(5) *Area-weighted mean patch size* quantifies the sum, across all patches of a particular LC/LU, of patch area multiplied by proportional abundance of the patch. Since this metric weights each patch by its size relative to the total area of that particular LC/LU, larger patches exert greater influence than smaller patches, reducing the effects of extremely small patches.
(6) *Area-weighted mean edge contrast* (percentage) quantifies the amount of contrast between adjacent LC/LU patches. In this application, contrast is defined as physical characteristics of differing cover types influencing nutrient transport. The metric quantifies the functional edge based on predetermined contrast weights assigned to pairwise comparisons of LC/LU types giving greater influence to larger patches.
(7) *Area-weighted mean Euclidean nearest neighbor distance* quantifies the shortest distance from one patch to the next patch of the same LC/LU type, weighted in favor of larger patch sizes.

2.3. The SPARROW model

SPARROW estimates TN and TP loadings (mass for a specified time) and yields (mass for a specified time normalized for drainage area) from spatially referenced watershed networks using source, land-to-water delivery, and stream and reservoir decay variables. The model is most frequently parameterized using average watershed-wide conditions for 1 specific year that represents a "snapshop" in time and is therefore not event-based (unlike HSPF). However, this allows for SPARROW to predict loadings and yields at a substantially higher number of points throughout these networks than HSPF is capable of by using linked nested stream reaches and their contributing catchment areas that are greatly smaller in magnitude. Catchments surrounding these nested reaches are denoted as $J(i)$ and are the set of all reaches upstream that include reach i, except for those containing, or upstream of, monitoring stations of reach i (Fig. 2) (Alexander et al., 2002b). Unlike many other source-transport watershed models, SPARROW can simulate large watersheds using land-to-water delivery variables and simplified, yet process-based, descriptions of the sources (Schwarz et al., 2006).

Both point and non-point source variables resulting in river discharges into the receiving water body (in this case the Chesapeake Bay) are included. Land-to-water delivery variables describe properties of the landscape relating climatic and other natural and human-induced surface processes affecting non-point N and P transport to streams. Stream decay is described by first-order losses of TN and TP loadings along stream channels, whereas reservoir decay is described by attenuation factors that influence TN and TP losses through large lakes and reservoirs. SPARROW uses non-linear least squares regression to determine which variables are significant (p-value ≤ 0.05) at the (Chesapeake Bay) watershed stations.

Table 1
The 16 Chesapeake Bay watershed cover classes created from the 2000 Regional Earth Science Applications Center (RESAC) land cover/land use (LC/LU), % impervious surface area (ISA), and % tree cover (TC) maps.

2000 land cover class	Class number
Urban (≥10% ISA)	1
Non-urban (<10% ISA)	2
Urban/residential/recreational grasses	3
Extractive	4
Barren	5
Deciduous forest	6
Evergreen forest	7
Mixed (deciduous–evergreen) forest	8
Pasture/hay	9
Croplands	10
Natural grass	11
Deciduous wooded wetland	12
Evergreen wooded wetland	13
Emergent (sedge-herb) wetland	14
Non-forested (≤50% TC)	15
Forested (>50% TC)	16

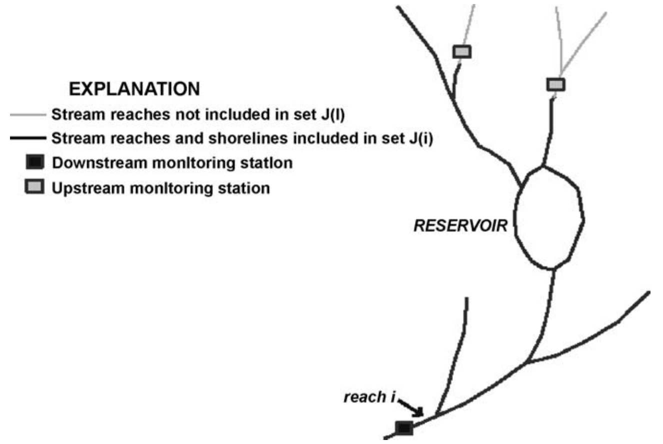

Fig. 2. Illustration of a set of nested stream reaches and reservoir shorelines in relation to monitoring stations. In model calibration, reach *i* refers to any reach containing a monitoring station. In model application, reach *i* refers to any reach for which a prediction can be made.

To assess model robustness, SPARROW utilizes a sensitivity analysis with Monte Carlo data resampling bootstrapping methods. The analysis calculates whether any coefficient has the wrong sign (Smith et al., 1997) using the mean coefficient value (bootstrap estimate), confidence interval, and probability. Coefficients for significant variables are generated in 200 separate model runs by resampling (with replacement) from the original data.

The structure of Version 3.0 Chesapeake Bay model (Brakebill and Preston, 2004), referred to as B & P, was used so that the overall topology of the stream network and B & P non-LC/LU variables, such as point sources, could be used. Variables not related to landscape properties were the most current (1997) watershed-wide estimated datasets available. In addition, this version most closely approximated the year (2000) of the RESAC landscape maps. The difference in this present application from B & P was that landscape metrics were added by replacing catchment-wide non-point nutrient land sources and creating new catchment and riparian stream buffer-wide land-to-water delivery variables in order to determine the total significance of LC/LU composition and configuration Riparian stream buffers are defined here as fixed, transitional areas between terrestrial landscapes and stream reaches created from the linked, spatially referenced watershed network. In Version 3.0, 2339 separate catchments averaging 71 km^2 were modeled (Fig. 3a) using the enhanced river reach file (E3RF1) (Brakebill and Preston, 2004).

The TN and TP models were calibrated with observations at 87 and 104 stream loading sites, respectively, collected in 1997 by federal and state agencies. Stream nutrient loadings were calculated from the data using a log-linear regression model know as ESTIMATOR (Cohn et al., 1989), which uses the 1950–2000 averages of daily stream discharge, specifying 1997 as the trend component (Brakebill and Preston, 2004).

2.4. Model calibration

Using the 2339 modeled catchments and their associated stream reaches, fixed riparian stream buffers of 31, 62, 125, 250, 500, and 1000 meters (m) (Fig. 3b) were specified for a total of 4678 land areas per model. A model run consisted of analyzing 2000 land cover classes within each of the 2339 catchments with the only differences being which land cover area within one of the six fixed riparian stream buffer areas was also analyzed. Using FRAGSTATS (McGarigal et al., 2002), five of the seven metrics (area-weighted mean radius of gyration, patch number, percentage of landscape, area-weighted mean edge contrast, and area-weighted mean Euclidean nearest neighbor distance) were created from the 16 cover classes at both catchment and riparian stream buffer width scales, adding 160 new variables per run evaluated for land-to-water delivery significance.

The sixth metric (contagion) was calculated for land cover classes in 2000 at the catchment and the six riparian stream buffer widths. The values were calculated per map, not using LC/LU data cross-referenced between the other two maps. Contagion was calculated at the landscape map level between the cover classes of: (1) non-urban (<10% ISA, class 1) and urban (≥10% ISA, class 2) in the % ISA map, (2) the 12 remaining non-urban classes (classes 3-

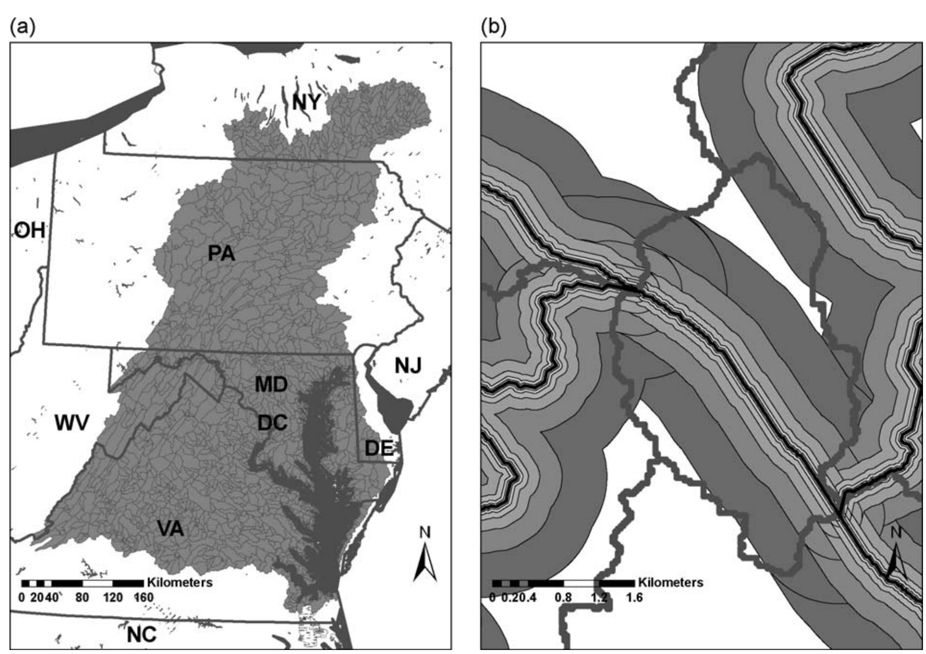

Fig. 3. Map of: (a) 2339 United States Geological Survey (USGS) Chesapeake Bay total nitrogen (TN) and total phosphorus (TP) SPAtially Referenced Regressions On Watershed attributes (SPARROW) model catchments used and (b) example Chesapeake Bay catchment with six fixed riparian stream buffer width areas of 31, 62, 125, 250, 500, and 1000 m surrounding stream reach.

14), and (3) non-forested (≤50% TC, class 15) and forested (>50% TC, class 16) from the % TC map at both catchment and riparian stream buffer width scales to add six more variables. By adding in the six contagion variables, a total of 166 new variables were evaluated for each TN and TP model run.

Finally, the 1997 B & P model urban (TN and TP models) and non-agricultural/non-urban (TP model only) areas were replaced by the area-weighted mean patch size for 2000 urban (≥10% ISA) and non-agricultural/non-urban land. Non-agricultural/non-urban land area in the B & P TP model was modified here for new TP models by formation of area-weighted mean non-agricultural/non-urban patch sizes obtained by subtracting area-weighted mean cropland patch sizes (class 10) from area-weighted mean non-urban (<10% ISA) patch sizes (class 2). By adding catchment-wide area-weighted mean urban (≥10% ISA) patch sizes (TN and TP models), along with area-weighted mean non-agricultural/non-urban patch sizes (TP model only) as non-point source regions, the final number of variables increased to 167 and 168 for each TN and TP model run, respectively.

The area-weighted mean patch size metric for the 16 landscape classes was not evaluated for land-to-water delivery significance since it could not be normalized for catchment and riparian stream buffer width area. Any type of land-to-water delivery variable directly correlated with catchment and riparian stream buffer width size would tend to confuse the relationship between scale-dependent, non-point source variables and non-point N and P stream loadings.

3. Results

3.1. TN model

Of the six models that used riparian stream buffers, the 31 m buffer out-performed all other simulations (yield r^2 0.9366; root mean squared error (RMSE) 0.2407) (Table 2). The 31 m model explained nearly 94% of variations in the mean annual TN yield resulting in a RMSE of 24%. The r^2 between observed and predicted loadings at the 87 Chesapeake Bay TN monitoring stations was 0.9733 (Fig. 4a). Buffer widths of 62–1000 m had lower yield r^2 and higher RMSE values, but the same significant coefficients. Of the 167 landscape variables tested for either source or land-to-water delivery potential in the 31 m TN model, only five were significantly related to non-point N sources or delivery to streams. The five metrics were: area-weighted mean urban (≥10% ISA) patch size (source), percentage of extractive land (land-to-water delivery), area-weighted mean edge contrast of deciduous forest (land-to-water delivery), percentage of cropland (land-to-water delivery), and percentage of evergreen forest within the riparian stream buffer (land-to-water delivery) (Table 3). The only difference between the 31 m model and the

Table 2
Comparison of yield coefficient of determination (r^2)and root mean square error (RMSE) values between the Brakebill and Preston, 2004 (1997 B & P) and the 2000 RESAC 31–1000 meter (m) TN and TP models.

Model run	Model yield r^2	Model RMSE
1997 B & P TN	0.9073	0.2834
2000 RESAC 31 m TN	0.9366	0.2407
2000 RESAC 62 m TN	0.9332	0.2454
2000 RESAC 125 m TN	0.9332	0.2454
2000 RESAC 250 m TN	0.9332	0.2454
2000 RESAC 500 m TN	0.9332	0.2454
2000 RESAC 1000 m TN	0.9332	0.2454
1997 B & P TP	0.7413	0.3257
2000 RESAC 31 m TP	0.7503	0.3126
2000 RESAC 62 m TP	0.7457	0.3246
2000 RESAC 125 m TP	0.7353	0.3329
2000 RESAC 250 m TP	0.7262	0.3368
2000 RESAC 500 m TP	0.7220	0.3393
2000 RESAC 1000 m TP	0.7209	0.3400

Table 3
Comparison of the significant (p-value ≤ 0.05) landscape metrics in the 2000 RESAC 31 m TN and TP models.

2000 RESAC 31 m Model	Significant (p-value ≤ 0.05) landscape metric variables	p-Value
TN	Area-weighted mean urban (≥10% ISA) patch size (source)	7.2×10^{-7}
	Percentage of cropland (land-to-water delivery)	1.1×10^{-4}
	Percentage of extractive land (land-to-water delivery)	7.4×10^{-4}
	Area-weighted mean edge contrast of deciduous forest (land-to-water delivery)	7.2×10^{-3}
	Percentage of evergreen forest within the riparian stream buffer (land-to-water delivery)	4.7×10^{-2}
TP	Area-weighted mean non-agricultural/non-urban patch size (source)	5.8×10^{-13}
	Percentage of barren land within the riparian stream buffer (land-to-water delivery)	1.2×10^{-6}
	Area-weighted mean urban (≥10% ISA) patch size (source)	1.0×10^{-4}

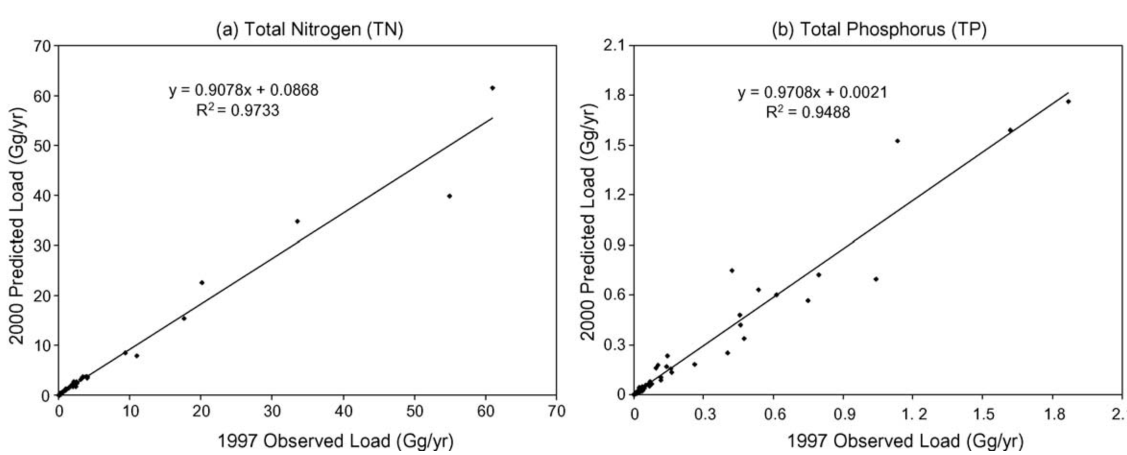

Fig. 4. Comparison of the correlation between the observed versus predicted loadings (gigagrams per year (Gg/yr)) in the: (a) 2000 31 m TN model utilizing 87 Chesapeake Bay water quality nitrogen (N) monitoring stations and (b) 2000 31 m TP model utilizing 104 Chesapeake Bay water quality phosphorus (P) monitoring stations. 1 gigagram (Gg) = 1,000,000 kilograms (kg).

Table 4
All significant (p-value $\leq$ 0.05) variables in the 1997 B & P and 2000 TN models using 31–1000 m riparian stream buffer widths with model coefficients and p-values (in parentheses).

Variable (units)	Model run (year)	B & P (1997)	RESAC (2000)					
			31 m	62 m	125 m	250 m	500 m	1000 m
	Yield r^2	0.9073	0.9366	0.9332	0.9332	0.9332	0.9332	0.9332
	RMSE	0.2834	0.2406	0.2454	0.2454	0.2454	0.2454	0.2454
	Model category							
Point sources (kg/yr)	Nitrogen source	1.530 (1.1×10^{-4})	1.173 (1.2×10^{-4})	1.169 (1.6×10^{-4})	1.169 (1.6×10^{-4})	1.169 (1.6×10^{-4})	1.169 (1.6×10^{-4})	1.169 (1.6×10^{-4})
Applied fertilizer (kg/yr)	Nitrogen source	0.294 (6.8×10^{-13})	0.175 (3.9×10^{-6})	0.194 (1.0×10^{-6})	0.194 (1.0×10^{-6})	0.194 (1.0×10^{-6})	0.194 (1.0×10^{-6})	0.194 (1.0×10^{-6})
Atmospheric deposition (kg/yr)	Nitrogen source	0.215 (3.5×10^{-7})	0.492 (2.0×10^{-7})	0.476 (4.0×10^{-7})	0.476 (4.0×10^{-7})	0.476 (4.0×10^{-7})	0.476 (4.0×10^{-7})	0.476 (4.0×10^{-7})
Applied manure (kg/yr)	Nitrogen source	0.065 (7.3×10^{-3})	0.078 (7.7×10^{-4})	0.087 (5.1×10^{-4})	0.087 (5.1×10^{-4})	0.087 (5.1×10^{-4})	0.087 (5.1×10^{-4})	0.087 (5.1×10^{-4})
Urban land (kg/ha/yr)	Nitrogen source	9.157 (8.7×10^{-6})	ONU	ONU	ONU	ONU	ONU	ONU
Area-weighted mean urban ($\geq$10% ISA) patch size* (kg/ha/yr)	Nitrogen source	MNU	24.885 (7.2×10^{-7})	23.200 (1.2×10^{-6})	23.200 (1.2×10^{-6})	23.200 (1.2×10^{-6})	23.200 ($1.2 \times \times 10^{-6}$)	23.200 (1.2×10^{-6})
Percentage of coastal plain (%)	Landscape delivery	−0.735 (1.6×10^{-7})	−0.729 (4.1×10^{-8})	−0.679 (1.9×10^{-7})	−0.679 (1.9×10^{-7})	−0.679 (1.9×10^{-7})	−0.679 (1.9×10^{-7})	−0.679 (1.9×10^{-7})
Percentage of extractive land* (%)	Landscape delivery	MNU	0.270 (7.4×10^{-4})	0.283 (6.5×10^{-4})	0.283 (6.5×10^{-4})	0.283 (6.5×10^{-4})	0.283 (6.5×10^{-4})	0.283 (6.5×10^{-4})
Area-weighted mean edge contrast of deciduous forest* (%)	Landscape delivery	MNU	0.014 (7.2×10^{-3})	0.011 (3.1×10^{-2})	0.011 (3.1×10^{-2})	0.011 (3.1×10^{-2})	0.011 (3.1×10^{-2})	0.011 (3.1×10^{-2})
Percentage of cropland* (%)	Landscape delivery	MNU	0.021 (1.1×10^{-4})	0.020 (2.0×10^{-4})	0.020 (2.0×10^{-4})	0.020 (2.0×10^{-4})	0.020 (2.0×10^{-4})	0.020 (2.0×10^{-4})
Percentage of evergreen forest within the riparian stream buffer* (%)	Landscape delivery	MNU	0.013 (4.7×10^{-2})	MIS	MIS	MIS	MIS	MIS
Small streams (m/day)	Stream decay	0.375 (1.8×10^{-2})	0.249 (5.5×10^{-2})	0.299 (2.4×10^{-2})	0.299 (2.4×10^{-2})	0.299 (2.4×10^{-2})	0.299 (2.4×10^{-2})	0.299 (2.4×10^{-2})
Intermediate streams (m/day)	Stream decay	0.135 (2.2×10^{-1})	0.090 (3.2×10^{-1})	0.088 (3.4×10^{-1})	0.088 (3.4×10^{-1})	0.088 (3.4×10^{-1})	0.088 (3.4×10^{-1})	0.088 (3.4×10^{-1})
Large streams (m/day)	Stream decay	0.031 (5.4×10^{-1})	0.030 (4.8×10^{-1})	0.028 (5.1×10^{-1})	0.028 (5.1×10^{-1})	0.028 (5.1×10^{-1})	0.028 (5.1×10^{-1})	0.028 (5.1×10^{-1})
Reservoir (m/yr)	Reservoir decay	19.036 (2.8×10^{-2})	14.224 (2.3×10^{-2})	14.466 (2.3×10^{-2})	14.466 (2.3×10^{-2})	14.466 (2.3×10^{-2})	14.466 (2.3×10^{-2})	14.466 (2.3×10^{-2})

* Denotes all landscape metrics found to be significant. ONU indicates original land source area "not utilized" as a result of being replaced with the new surrogate landscape source area metric in 2000 model runs. MNU indicates new landscape source area metric and landscape land-to-water delivery metrics "not utilized" in original 1997 B & P model run. MIS indicates new landscape land-to-water metric determined to be "insignificant" (p-value > 0.05) for that 2000 model run.

Table 5
Sensitivity analysis comparison of all significant (p-value ≤ 0.05) estimated variables between initial parametric and averaged bootstrapped coefficient estimates in 2000 31 m TN model.

Variable (units)	Model category	Model run (year): RESAC (2000)	
		31 M initial parametric	31 M averaged bootstrapped
Point sources (kg/yr)	Nitrogen source	1.173	1.189
Applied fertilizer (kg/yr)	Nitrogen source	0.175	0.170
Atmospheric deposition (kg/yr)	Nitrogen source	0.492	0.508
Applied manure (kg/yr)	Nitrogen source	0.078	0.080
Area-weighted mean urban (≥10% ISA) patch size* (kg/ha/yr)	Nitrogen source	24.885	28.555
Percentage of coastal plain (%)	Landscape delivery	−0.729	−0.757
Percentage of extractive land* (%)	Landscape delivery	0.270	0.280
Area-weighted mean edge contrast of deciduous forest* (%)	Landscape delivery	0.014	0.015
Percentage of cropland* (%)	Landscape delivery	0.021	0.021
Percentage of evergreen forest within the riparian stream buffer* (%)	Landscape delivery	0.013	0.019
Small streams (m/day)	Stream decay	0.249	0.261
Intermediate streams (m/day)	Stream decay	0.090	0.103
Large streams (m/day)	Stream decay	0.030	0.037
Reservoir (m/yr)	Reservoir decay	14.224	13.669

* Denotes all landscape metrics found to be significant.

other buffer widths was the highly significant (p-value = 4.87×10^{-2}) effect of percentage of evergreen forest (Table 4). The percentage of evergreen forest in models of buffer widths of 62–1000 m was omitted as a land-to-water delivery variable ($p > 0.05$). Sensitivity analysis results comparing initial parametric with a final set of averaged bootstrapped coefficient estimates showed good agreement between the two for all significant variables (Table 5).

Of the 2339 catchments in the 31 m model, the largest TN yields (>18 kg/ha/yr) were identified in: the lower Susquehanna Basin containing cities such as Harrisburg, Lancaster, and York (PA); along tributaries of the middle Potomac Basin in north central MD; the eastern shore of MD; and southwestern DE (Fig. 5a). Smaller areas of high locally generated TN yields were also found near the urban areas of DC and Richmond (VA). Although much attenuation occurred after accounting for stream and reservoir loss processes, there were only local differences in the amount of largest TN yields (>18 kg/ha/yr) delivered to the estuary (Fig. 5b). The highest locally generated urban (≥10% ISA) patch size N yields (>0.99 kg/ha/yr) per catchment were associated with the major urban centers of: DC; Baltimore (MD); Scranton/Wilkes-Barre, Harrisburg, Lancaster, and York (PA); Richmond, Petersburg, and Norfolk-Virginia Beach-Newport News (VA); and Elmira and Binghamton (NY) (Fig. 6a). Stream and reservoir decay reduced area-weighted mean urban (≥10% ISA) patch size N yield per catchment. However, largest yields (>0.99 kg/ha/yr) to the estuary were still shown to originate from these areas (Fig. 6b).

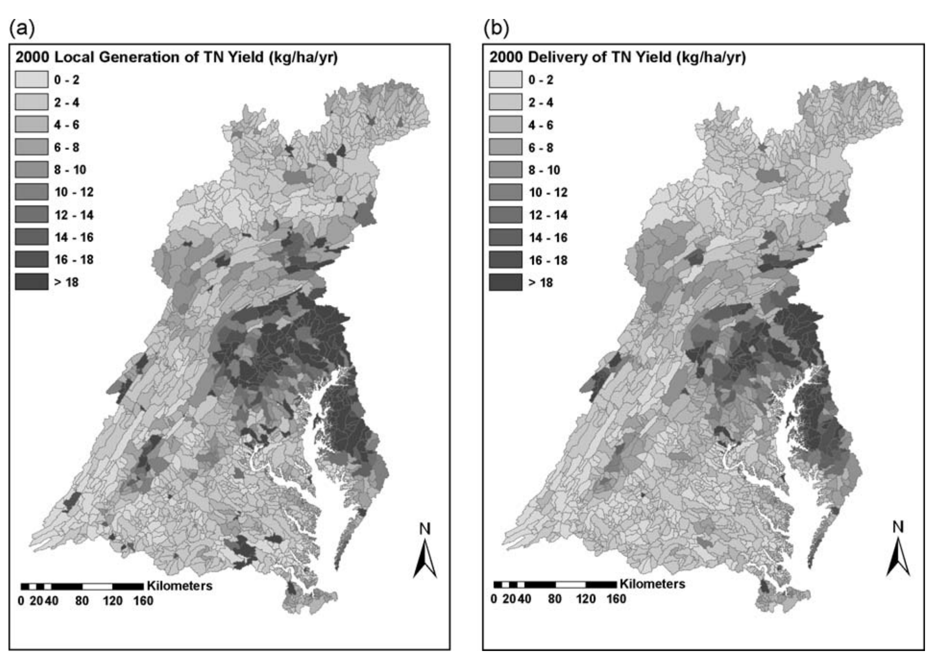

Fig. 5. Per catchment estimated TN yield (kilograms per hectare per year (kg/ha/yr)) map from the 2000 31 m model of: (a) local generation and (b) delivery to the Chesapeake Bay estuary.

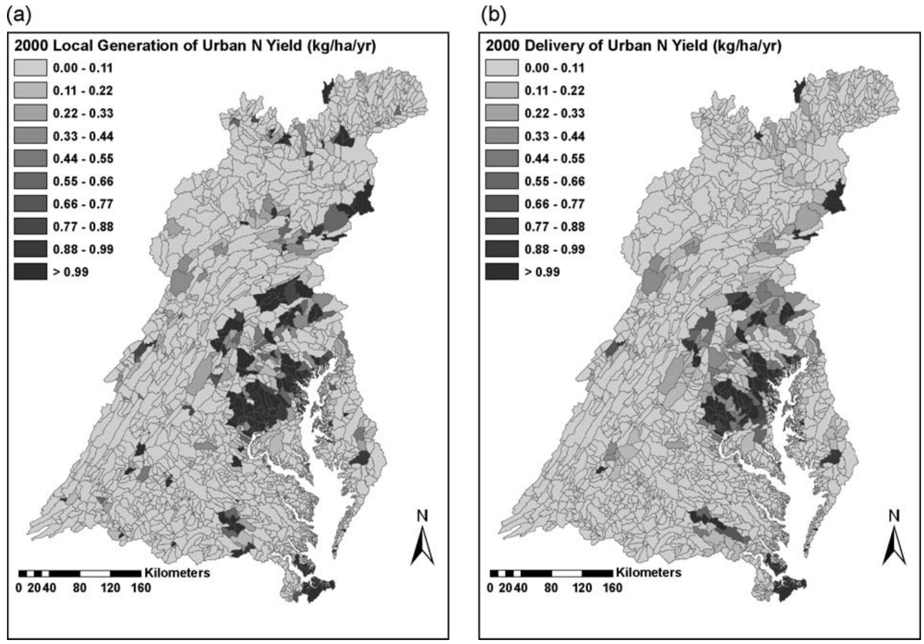

Fig. 6. Per catchment estimated area-weighted mean urban (≥10% ISA) patch size N yield (kg/ha/yr) map from the 2000 31 m model of: (a) local generation and (b) delivery to the Chesapeake Bay estuary.

3.2. TP model

As in the case of the TN models, restriction of metrics to the 31 m riparian stream buffer gave the best results. This model also had the highest yield r^2 (0.7503) and lowest RMSE (0.3216) (Table 2). The 31 m model explained about 75% of variation in the mean annual TP yield, a small improvement over the 62 m model. The r^2 between observed and predicted loadings at the 104 TP monitoring stations was 0.9488 (Fig. 4b). Model significance decreased with each of the wider buffers.

In the 31 m model, of 168 landscape metric variables, only three were significantly related to non-point P sources or delivery processes (Table 3). Within the riparian stream buffer, the percentage of barren land was the only significant land-to-water delivery metric (Table 6). However, significance of this variable fell as the width of the riparian stream buffer increased. Comparisons between the initial parametric and the final set of averaged bootstrapped coefficient estimates indicated little to no deviation for all significant variables (Table 7).

A map of locally generated TP yields showed that highest yields (>0.99 kg/ha/yr) were found in: the central and lower Susquehanna Basin near Scranton/Wilkes Barre, Harrisburg, Lancaster, and York (PA); central MD; Richmond and Petersburg (VA) in the middle-to-lower James Basin (Fig. 7a). After accounting for stream and reservoir losses, areas with the highest TP yields (>0.99 kg/ha/yr) delivered to the estuary were significantly reduced, with the exception of near Lancaster (PA) (Fig. 7b). A map of locally generated area-weighted mean urban (≥10% ISA) patch size P yields per catchment showed that higher values (>0.45 kg/ha/yr) were estimated in: Harrisburg (PA); DC; Baltimore (MD); and Richmond and Norfolk-Virginia Beach-Newport News (VA) (Fig. 8a). Highest delivered yields (>0.45 kg/ha/yr) were also found in these urban municipalities (Fig. 8b). Finally, although lower in magnitude, the greatest locally generated area-weighted mean non-agricultural/non-urban patch size P yields per catchment (>0.27 kg/ha/yr) were in northern and central VA (Fig. 9a). The largest delivered area-weighted mean non-agricultural/non-urban patch size P yields (>0.27 kg/ha/yr) was also from these areas (Fig. 9b).

4. Discussion

4.1. Effects of non-urban and urban LC/LU on TN and TP runoff to the Chesapeake Bay

The 2000 area-weighted mean urban (≥10% ISA) patch size derived from the RESAC map was found to be well correlated with the 1997 NLCD LC, as used by B & P, which suggests that the new parameterization did not change the fundamental structure of B & P, and so the use here of non-LC/LU elements of B & P was justified (Fig. 10a). Numerous studies (Bannerman et al., 1993; Rushton, 2001; Sonada et al., 2001; Stow et al., 2001; Line et al., 2002; Shinya et al., 2003; Coulter et al., 2004; Groffman et al., 2004; Law et al., 2004; Osmond and Hardy, 2004; Caccia and Boyer, 2005; Erickson et al., 2005; Wakida and Lerner, 2005, 2006; Williams et al., 2005; Gilbert and Clausen, 2006) have found that non-point N and P generated from low, medium, and high intensity developed, as well as transportation LC/LU classes are linked to stream loadings. The 1997 non-agricultural/non-urban land used by B & P was also well correlated with the 2000 area-weighted mean non-agricultural/non-urban patch size derived from RESAC in the 31 m model (Fig. 10b).

Nearly 25 kg of non-point N in the 31 m TN model, as compared to close to 1 kg of non-point P in the 31 m TP model, were estimated to be generated and measured from streams draining the estuary from each 1 ha area-weighted mean urban (≥10% ISA) patch size annually (Tables 4 and 6). The 31 m TN model coefficient value was well within the expected range of export values for all urban land use yields (3–40 kg/ha/yr) (Schwarz et al., 2006). The largest area-weighted mean urban (≥10% ISA) patch sizes (>270 ha) were identified in: DC; Baltimore (MD); Scranton/Wilkes-Barre, Harrisburg, Lancaster, and York (PA); Richmond, Petersburg and Norfolk-Virginia Beach-Newport News (VA); and Elmira and Binghamton (NY) (Fig. 11a).

Just over 0.1 kg of non-point P in the 31 m model was estimated to be generated and measured from streams draining the Chesapeake Bay from each 1 ha of the area-weighted mean non-agricultural/non-urban patch size annually (Table 6). The highest area-weighted mean non-agricultural/non-urban patch sizes per

Table 6
All significant (p-value $\leq$ 0.05) estimated variables between the 1997 B & P and 2000 TP models using 31–1000 m riparian stream buffer widths with model coefficients and p-values (in parentheses).

Variable (units)	Model category	B & P (1997)	RESAC (2000) 31 m	62 m	125 m	250 m	500 m	1000 m
Yield r^2		0.7413	0.7503	0.7457	0.7353	0.7262	0.7220	0.7209
RMSE		0.3257	0.3216	0.3246	0.3330	0.3367	0.3394	0.3400
Point sources (kg/yr)	Phosphorus source	0.673 (4.7×10^{-6})	0.738 (1.3×10^{-6})	0.743 (1.4×10^{-6})	0.710 (5.4×10^{-6})	0.734 (3.4×10^{-6})	0.724 (4.5×10^{-6})	0.725 (4.5×10^{-6})
Applied fertilizer (kg/yr)	Phosphorus source	0.016 (3.3×10^{-4})	0.016 (1.1×10^{-3})	0.016 (1.1×10^{-3})	0.019 (3.4×10^{-4})	0.016 (1.9×10^{-3})	0.016 (1.8×10^{-3})	0.016 (1.9×10^{-3})
Applied manure (kg/yr)	Phosphorus source	0.007 (4.5×10^{-2})	0.008 (3.0×10^{-2})	0.008 (3.5×10^{-2})	0.009 (2.9×10^{-2})	0.008 (3.6×10^{-2})	0.008 (3.9×10^{-2})	0.008 (3.8×10^{-2})
Non-agricultural/non-urban land (kg/ha/yr)	Phosphorus source	0.093 (9.0×10^{-13})	ONU	ONU	ONU	ONU	ONU	ONU
Area-weighted mean non-agricultural/ non-urban patch size* (kg/ha/yr)	Phosphorus source	MNU	0.110 (5.8×10^{-13})	0.110 (1.1×10^{-12})	0.094 (2.5×10^{-11})	0.105 (6.6×10^{-12})	0.104 (7.6×10^{-12})	0.102 (6.6×10^{-12})
Urban land (kg/ha/yr)	Phosphorus source	0.442 (7.8×10^{-5})	ONU	ONU	ONU	ONU	ONU	ONU
Area-weighted mean urban ($\geq$10% ISA) patch size* (kg/ha/yr)	Phosphorus source	MNU	0.921 (1.0×10^{-4})	0.893 (1.3×10^{-4})	0.975 (1.1×10^{-4})	0.873 (2.3×10^{-4})	0.861 (2.8×10^{-4})	0.867 (2.8×10^{-4})
Percentage of barren land within the riparian stream buffer* (%)	Landscape delivery	MNU	0.281 (1.2×10^{-6})	0.279 (6.1×10^{-5})	0.213 (1.8×10^{-3})	0.167 (7.0×10^{-3})	0.132 (1.6×10^{-2})	0.114 (2.0×10^{-2})
Small streams (m/day)	Stream decay	−0.260 (4.9×10^{-2})	−0.198 (1.3×10^{-1})	−0.199 (1.4×10^{-1})	−0.210 (1.3×10^{-1})	−0.194 (1.7×10^{-1})	−0.191 (1.9×10^{-1})	−0.184 (2.1×10^{-1})
Intermediate streams (m/day)	Stream decay	0.028 (7.9×10^{-1})	0.150 (1.9×10^{-1})	0.144 (2.1×10^{-1})	0.137 (2.4×10^{-1})	0.095 (4.1×10^{-1})	0.082 (4.8×10^{-1})	0.071 (5.3×10^{-1})
Large streams (m/day)	Stream decay	0.039 (4.6×10^{-1})	0.034 (5.2×10^{-1})	0.035 (5.1×10^{-1})	0.053 (3.5×10^{-1})	0.037 (5.0×10^{-1})	0.037 (5.1×10^{-1})	0.038 (5.0×10^{-1})
Reservoir (m/yr)	Reservoir decay	17.004 (5.4×10^{-2})	19.019 (5.7×10^{-2})	18.473 (6.3×10^{-2})	17.669 (7.5×10^{-2})	19.611 (6.1×10^{-2})	19.965 (5.9×10^{-2})	19.700 (5.8×10^{-2})

* Denotes all landscape metrics found to be significant. ONU indicates original land source areas "not utilized" as a result of being replaced with the new surrogate landscape source area metrics in 2000 model runs. MNU indicates new landscape source area metrics and landscape land-to-water delivery metric "not utilized" in original 1997 B & P model run.

Table 7
Sensitivity analysis comparison of all significant (p-value $\leq$ 0.05) estimated variables between initial parametric and averaged bootstrapped coefficient estimates in 2000 31 m TP model.

Variable (units)	Model category	Model run (year): RESAC (2000) 31 M initial parametric	31 M averaged bootstrapped
Point sources (kg/yr)	Phosphorus source	0.738	0.738
Applied fertilizer (kg/yr)	Phosphorus source	0.016	0.016
Applied manure (kg/yr)	Phosphorus source	0.008	0.008
Area-weighted mean non-agricultural/ non-urban patch size* (kg/ha/yr)	Phosphorus source	0.110	0.110
Area-weighted mean urban ($\geq$10% ISA) patch size* (kg/ha/yr)	Phosphorus source	0.921	1.139
Percentage of barren land within the riparian stream buffer* (%)	Landscape delivery	0.281	0.277
Small streams (m/day)	Stream decay	−0.198	−0.231
Intermediate streams (m/day)	Stream decay	0.150	0.138
Large streams (m/day)	Stream decay	0.034	0.044
Reservoir (m/yr)	Reservoir decay	19.019	20.529

* Denotes all landscape metrics found to be significant.

catchment (>27,000 ha) were located in PA and western VA (Fig. 11b).

For every one percent of extractive land composition in a catchment, a 0.27% increase in delivery from all non-point N sources to streams draining the estuary was estimated. Characteristics associated with extractive land may help explain this. Low infiltration capacities tied to decreased hydraulic conductivity (the ability of a porous medium to transmit a specific fluid under a unit hydraulic gradient) (Ward and Trimble, 2004) of mine soils that increase overland runoff have been found throughout the watershed's PA tributaries (Ritter and Gardner, 1993; Guebert and Gardner, 2001). Furthermore N-fixing trees, such as black locust (*Robinia pseudoacacia*), used in mine spoil reclamation in the Susquehanna Basin (Bruns, 2005) may also increase non-point N stream delivery. The highest percentages of extractive land per catchment (>4.5%) were found in central PA, western MD, and northeastern WV (Fig. 12a).

Area-weighted mean edge contrast of deciduous forest measures the contrast between the eleven non-urban LC/LU classes and deciduous forest in the LC/LU map. Greatest differences in this metric were between deciduous forest and urban/residential/recreational grasses, extractive, barren, pasture/hay, croplands, and natural grass. The greater the incidence of dissimilar LC/LU classes configured around deciduous forest, the higher the area-weighted mean edge contrast. This metric is also related to forest fragmentation. For each one percent of the area-weighted mean edge contrast of deciduous forest in a catchment, delivery from all non-point N sources to streams draining the estuary was estimated to increase by 0.014%. Fragmentation-related increases in runoff based upon observed lower hydraulic conductivities in nearby non-forested LC/LU classes, as compared to forested LC/LU classes, have been found elsewhere (Chandler and Walter, 1998; Giambelluca, 2002; Ziegler et al., 2004a, 2006, 2007; Zimmermann et al., 2006). The highest area-weighted mean edge contrasts of deciduous forest per catchment (>63%) were found in southeastern PA and northern MD (Fig. 12b).

For every 1% of cropland composition in a catchment, delivery from all non-point N sources to streams draining the estuary was

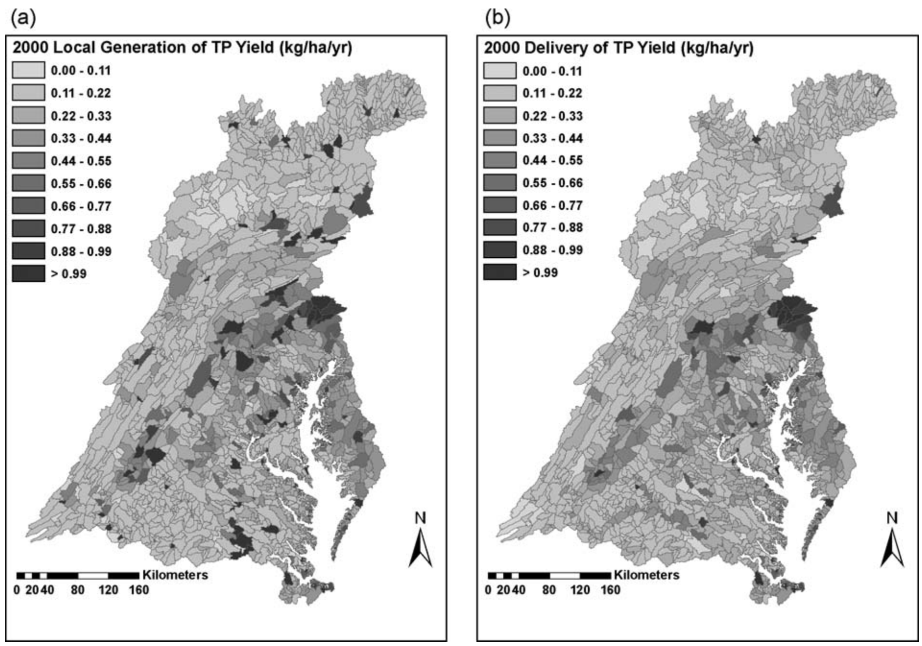

Fig. 7. Per catchment estimated TP yield (kg/ha/yr) map from the 2000 31 m model of: (a) local generation and (b) delivery to the Chesapeake Bay estuary.

estimated to increase by 0.021%. This may be a result of decreased hydraulic conductivity and increased runoff due to cultivation practices that may have contributed to applied fertilizer, manure and other non-point N delivery from these areas. Field compaction from tillage and machinery alone may promote surface sealing and overland runoff (Logsdon and Jaynes, 1996). The highest percentages of cropland per catchment (>45%) were in central and southeastern PA, the eastern shore of MD, and southwestern DE (Fig. 12c).

For every 1% of evergreen forest composition within riparian stream buffers, delivery from all non-point N sources to streams draining the estuary was estimated to increase by 0.013%. Increased overland and shallow subsurface N runoff correlated with greater evergreen forest has been found elsewhere, albeit in small catchments, resulting from decreased soil hydraulic conductivities (Allan et al., 1993; Allan and Roulet, 1994; Wetzel, 2003). A similar conclusion was also reached in North Carolina's (US) piedmont region where a greater proportion of forest in some riparian buffers increased N loadings to streams due to increased overland and shallow subsurface runoff linked to decreased soil hydraulic conductivity in these buffers (Verchot et al., 1997). Highest percentages of evergreen forest within riparian stream buffers per catchment (>22.5%) were in central PA, central and western VA, and south central NY (Fig. 12d).

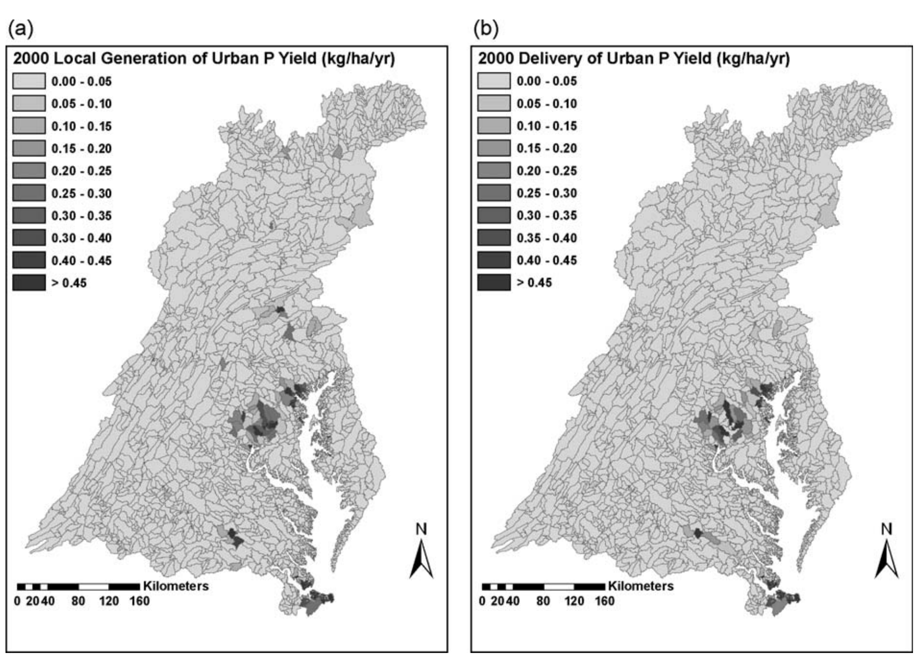

Fig. 8. Per catchment estimated area-weighted mean urban (≥10% ISA) patch size P yield (kg/ha/yr) map from the 2000 31 m model of: (a) local generation and (b) delivery to the Chesapeake Bay estuary.

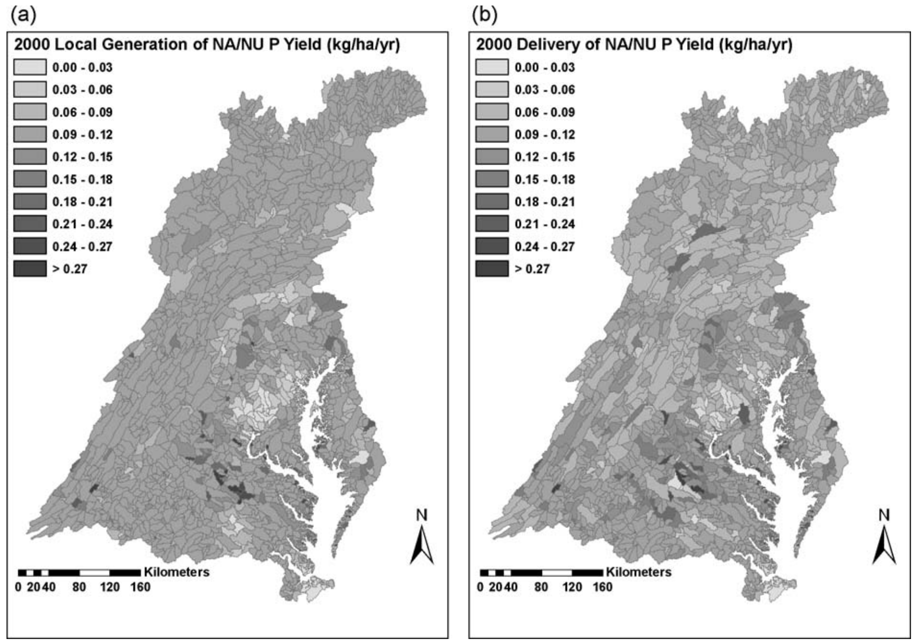

Fig. 9. Per catchment estimated area-weighted mean non-agricultural/non-urban (NA/NU) patch size P yield (kg/ha/yr) map from the 2000 31 m model of: (a) local generation and (b) delivery to the Chesapeake Bay estuary.

Finally, for every 1% of barren land composition within the riparian stream buffer, delivery from all non-point P sources to streams draining the estuary was estimated to increase by 0.281%. In other studies elsewhere, higher overland runoff related to greater compositions of barren land with lower hydraulic conductivity has been found at catchment scales (Ziegler and Giambelluca, 1997, 1998; Ziegler et al., 2001, 2004b; Assouline and Mualem, 2002; Perkins et al., 2007). In addition, a recent study conducted in Mississippi Basin (US) tributaries within the states of Arkansas and Missouri determined that compositions of this same landscape metric found significant in this study (percent barren land in the riparian stream buffer) were correlated to increase P in overland flow delivered to streams (Lopez et al., 2008). However, in that study, percent barren land in the riparian stream buffer was found to be significant at a fixed 120 m width. The highest percentages of barren land (>2.25%) in riparian stream buffers were in southeastern PA, central and the eastern shore of MD, southwestern DE, and central to south-eastern VA (Fig. 13).

4.2. Comparisons with B & P models of the Chesapeake Bay watershed

Since both the 31 m TN and TP SPARROW models and the B & P models are driven by the same non-LC/LU data, predictions of loadings and yields were similar. However, loading and yield allocations within similar catchments varied between the 31 m and B & P models. With the inclusion of the new additional explanatory RESAC-based LC/LU metric variables within the 31 m models, initial biases found in the B & P models of their original explanatory variables not accounting for the entire variability in all of the observed watershed-wide nutrient loading station estimates were slightly reduced. This was indicated by the increased yield r^2 and decreased RMSE values from the 31 m to the B & P TN and TP models (Table 2).

The TN annual loadings (kg/yr) estimated to enter the Chesapeake Bay from the 31 m model were 1.449×10^8, as compared to 1.480×10^8 generated from the B & P model, approximately 98% of the B & P model value. The mean annual TN yield (kg/ha/yr) per catchment draining directly to the

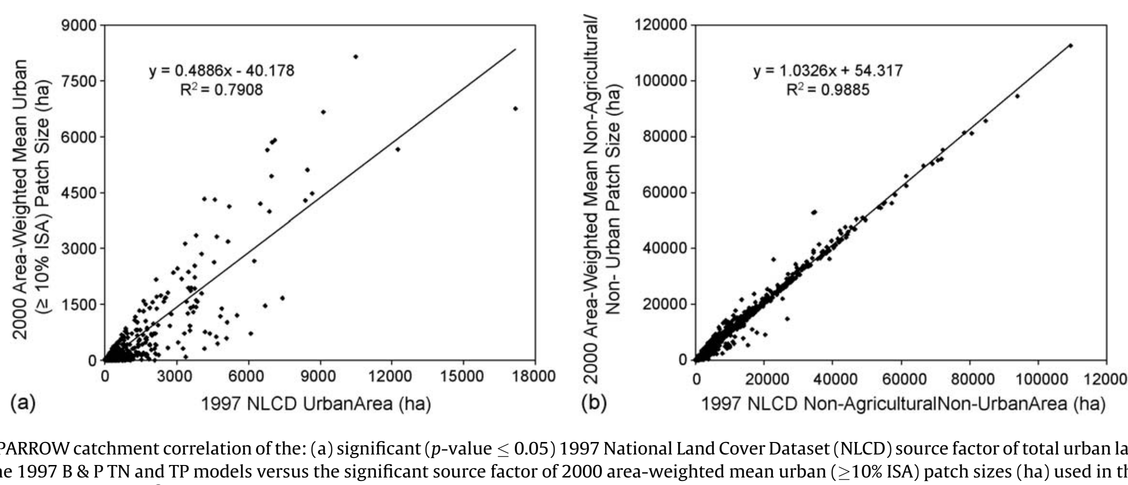

Fig. 10. 2339 SPARROW catchment correlation of the: (a) significant (p-value ≤ 0.05) 1997 National Land Cover Dataset (NLCD) source factor of total urban land area (hectares (ha)) used in the 1997 B & P TN and TP models versus the significant source factor of 2000 area-weighted mean urban (≥10% ISA) patch sizes (ha) used in the 2000 31 m (TN and TP) models with an observed r^2 of 0.7908 and (b) significant 1997 NLCD source factor of non-agricultural/non-urban land area (ha) used in the 1997 B & P TP model versus the significant source factor of 2000 area-weighted mean non-agricultural/non-urban patch sizes (ha) used in the 2000 31 m TP model with an observed r^2 of 0.9855.

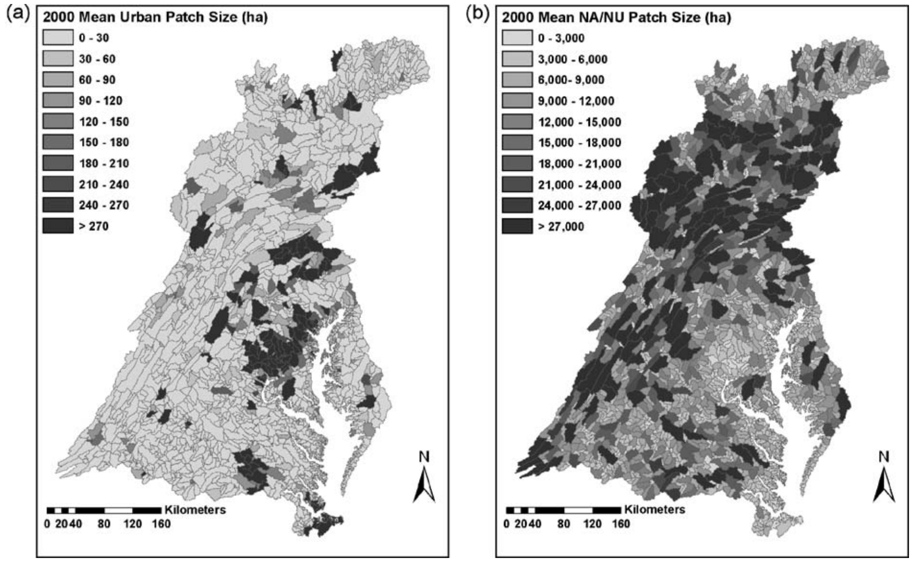

Fig. 11. Per catchment source factor metrics of: (a) area-weighted mean urban (≥10% ISA) patch size (ha) in the 2000 31 m total TN and TP models and (b) area-weighted mean non-agricultural/non-urban (NA/NU) patch size (ha) in the 2000 31 m TP model.

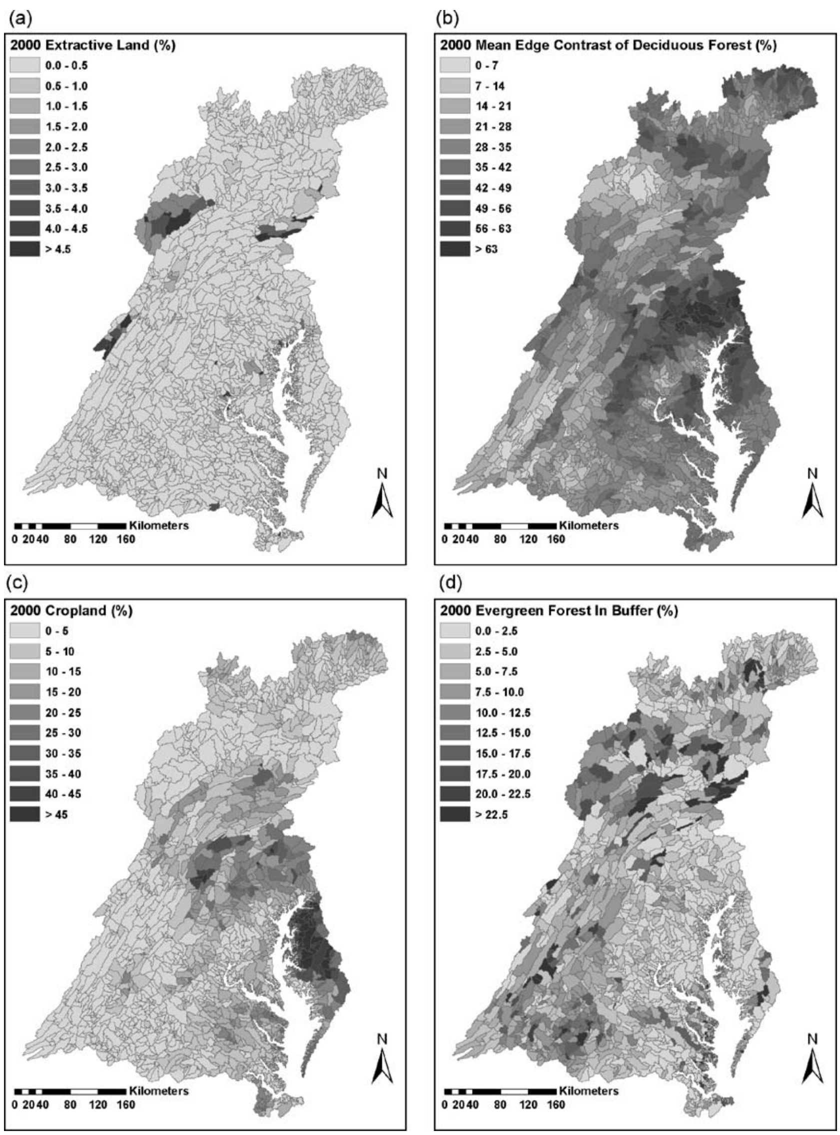

Fig. 12. Per catchment land-to-water delivery metrics of: (a) extractive land (%), (b) area-weighted mean edge contrast of deciduous forest (%), (c) cropland (%), and (d) evergreen forest in the riparian stream buffer (%) in the 2000 31 m TN model.

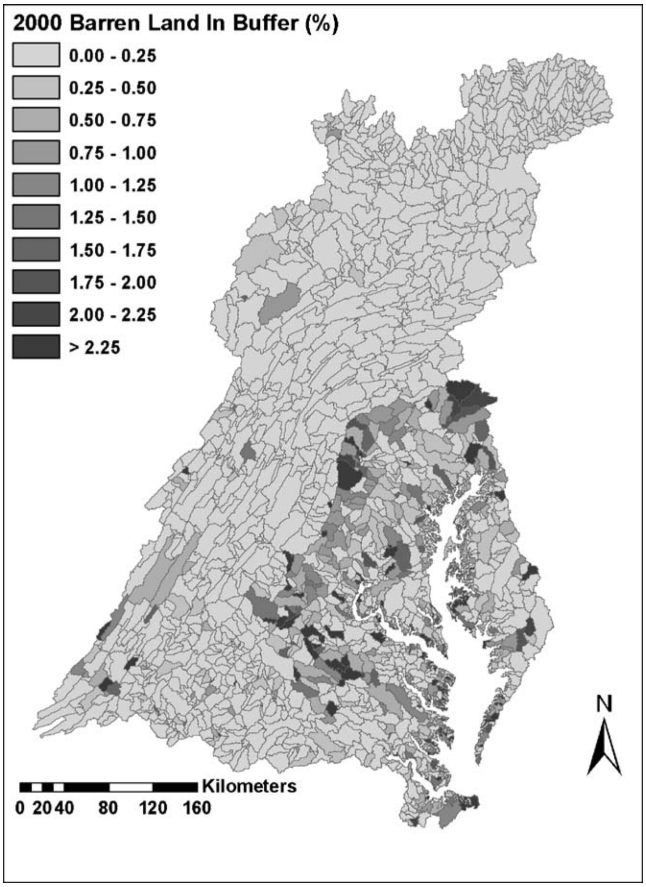

Fig. 13. Per catchment land-to-water delivery metric of barren land within the riparian stream buffer (%) in the 2000 31 m TP model.

Chesapeake Bay from the 31 m model was about 55.03, as compared to 62.58 from the B & P model. The largest increases (>3.00 kg/ha/yr) in delivered yield to the estuary per catchment from the new model to the B & P model were found near: central NY, central and southeastern PA, and northeastern MD in the upper, middle, and lower Susquehanna Basin; Cumberland (MD), northeastern WV, and northern VA in the upper-to-middle Potomac Basin; the eastern shore of MD; and DE (Fig. 14a). The largest decreases (>3.00 kg/ha/yr) in delivered yield to the estuary per catchment from the 31 m model to the B & P model were found near: DC in the lower Potomac Basin and Richmond and Petersburg (VA) in the middle-to-lower James Basin (Fig. 14a). The B & P and 31 m models showed close agreement in coefficients for LC/LU sources (urban land and area-weighted mean urban (≥10% ISA) patch size), non-LC/LU based sources (point, fertilizer and manure applications, and atmospheric N deposition), land-to-water delivery (coastal plain), stream decay (small, intermediate, and large), and reservoir decay (Table 4). A comparison of the 1997 B & P and 2000 31 m TN model loadings (kg/yr) in the six largest basins (James (27,019 km^2), Patuxent (2479 km^2), Potomac (38,000 km^2), Rappahannock (7405 km^2), Susquehanna (71,225 km^2), and York (6915 km^2)) had an r^2 value of 0.9974 (Fig. 15a). The York Basin is formed by the confluence of the Mattaponi and Pamunkey Basins in southeastern VA.

The TP annual loadings (kg/yr) estimated to reach the Chesapeake Bay estuary from the new model were 5.367×10^6 kg/yr versus 5.210×10^6 kg/yr estimated to reach the Bay from the B & P model, approximately 3% higher than the predicted loadings in the B & P model. The mean annual TP yield (kg/ha/yr) per catchment draining directly to the Chesapeake Bay from the 31 m model was about 2.38, as compared to 2.14 from the B & P model. The largest increases (>0.08 kg/ha/yr) in delivered yield to the Chesapeake Bay per catchment from the 31 m model to the B & P model were near: Lancaster and Harrisburg (PA) in the lower Susquehanna Basin; Baltimore (MD); Frederick and southern MD, DC, and northern VA in the middle-to-lower Potomac Basin; Fredericksburg (VA) in the middle Rappahannock Basin; central VA in the upper-to-middle Mattaponi and Pamunkey Basins; Norfolk-Virginia Beach-Newport News (VA) in the lower James Basin; the eastern shores of MD and VA; and DE (Fig. 14b). The largest decreases (>0.08 kg/ha/yr) in delivered yield to the estuary per catchment from the 31 m model to the B & P model were near: Baltimore (MD) and Lynchburg and Norfolk-Virginia Beach-Newport News (VA) in the upper-to-lower

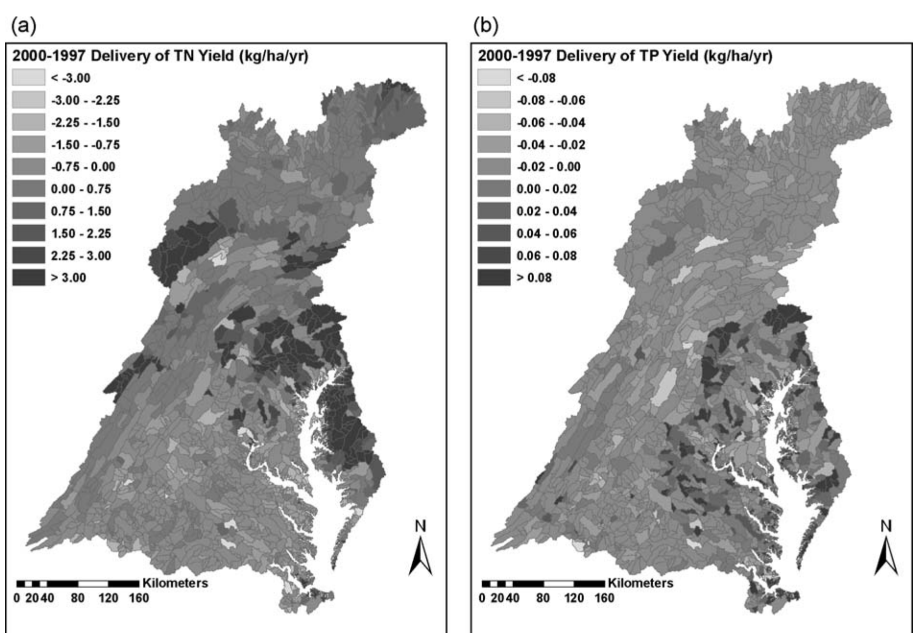

Fig. 14. Per catchment estimated difference between the 2000 31 m and 1997 B & P model in predicted yield (kg/ha/yr) delivered to the Chesapeake Bay estuary for: (a) TN and (b) TP.

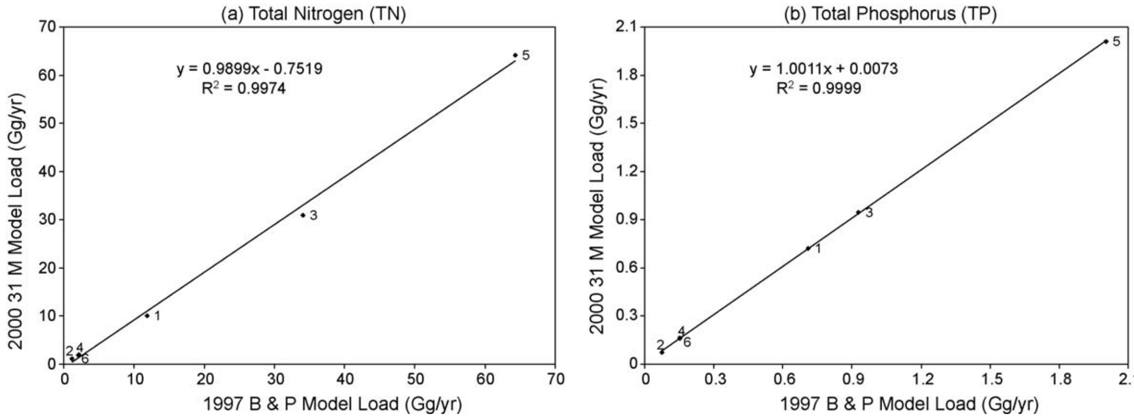

Fig. 15. Comparison of the 1997 B & P and 2000 31 m model estimated loadings (Gg/yr) for the James, Patuxent, Potomac, Rappahannock, Susquehanna, and the York Basins within the Chesapeake Bay watershed for: (a) TN and (b) TP. 1 = the James River Basin, 2 = the Patuxent River Basin, 3 = the Potomac River Basin, 4 = the Rappahannock River Basin, 5 = the Susquehanna River Basin, and 6 = the York River Basin.

James Basin (Fig. 14b). Similarly to the TN model, the comparisons of the significant coefficients of LC/LU sources (urban land, area-weighted mean urban (≥10% ISA) patch size, non-agricultural/non-urban land, and area-weighted mean non-agricultural/non-urban patch size), non-LC/LU based sources (point, fertilizer and manure applications), stream decay (small, intermediate, and large), and reservoir decay between the B & P and 31 m model were in close agreement (Table 6). The comparison of the 1997 B &P and 2000 31 m TP model loadings for the six largest basins in the watershed indicated an r^2 value of 0.9999 (Fig. 15b).

4.3. Comparisons between the Chesapeake Bay HSPF and SPARROW TN and TP models

The new TN and TP runoff model results were compared with the results of the Chesapeake Bay HSPF Phase 4.3 simulation parameterized upon 64–94 basins used from 1985 to 2000 (Wang et al., 2001; Chesapeake Bay Program, 2007). Chesapeake Bay HSPF modeling has been in progress since 1982 as a management tool for the estuary's restoration. In comparison with the mean 1985–1994 TN loading of 1.420×10^8 kg/yr estimated to enter the Chesapeake Bay from the Phase 4.3 HSPF simulation (Wang et al., 2001), the 2000 31 m TN model loadings were approximately 102% of the HSPF value. The 2000 31 m TN model loadings were nearly 112% of the 2000 Phase 4.3 HSPF TN model value of 1.292×10^8 kg/yr (Chesapeake Bay Program, 2007). The comparison between the estimated 2000 Phase 4.3 HSPF and the 31 m model TN loadings of the six largest basins in the watershed indicated a r^2 of 0.9858 (Fig. 16a). The close agreement between the SPARROW and the HSPF estimates suggest that the inclusion of new compositional and configuration representations of catchment and riparian stream buffer-wide urban and non-urban LC/LU in the SPARROW models could improve the precision of annual Chesapeake Bay TN runoff simulation.

The mean 1985–1994 estimated HSPF Phase 4.3 Bay TP loading was 9.991×10^6 kg/yr (Wang et al., 2001). The 2000 31 m TP model results were only 54% of this HSPF value. Furthermore, the 2000 31 m TP model loadings were approximately 62% of the estimated 2000 Phase 4.3 HSPF Bay TP loadings of 8.673×10^6 kg/yr (Chesapeake Bay Program, 2007). A comparison between the TP loadings for the 2000 Phase 4.3 HSPF and the SPARROW model in the six largest basins in the watershed indicated a much lower r^2 of 0.4479 (Fig. 16b). Although 2000 was 16% below the normal long-term mean Chesapeake Bay watershed-wide stream runoff (United States Geological Survey, 2001), these findings still suggest an underprediction of TP in SPARROW. However, the inclusion of new compositional metrics of watershed and riparian stream buffer-wide urban and non-urban LC/LU within SPARROW slightly improved the precision of predicted annual Chesapeake Bay-wide TP runoff against HSPF estimates.

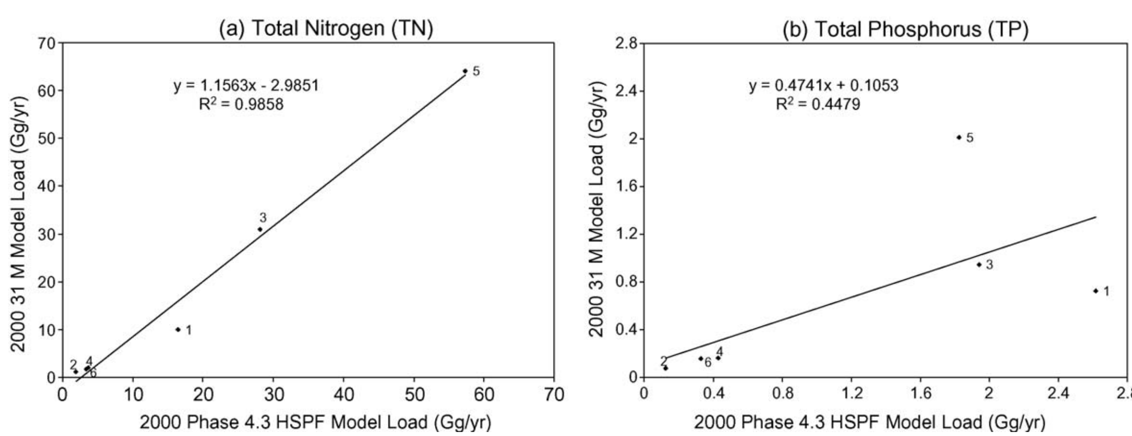

Fig. 16. Comparison of the 2000 Phase 4.3 Hydrologic Simulation Program-Fortran (HSPF) and 2000 31 m model estimated loadings (Gg/yr) for the James, Patuxent, Potomac, Rappahannock, Susquehanna, and the York Basins within the Chesapeake Bay watershed for: (a) TN and (b) TP. 1 = the James River Basin, 2 = the Patuxent River Basin, 3 = the Potomac River Basin, 4 = the Rappahannock River Basin, 5 = the Susquehanna River Basin, and 6 = the York River Basin.

5. Conclusions

This paper investigated the effect of LC/LU on simulations of regional nutrient loading to the Chesapeake Bay estuary using a modification of the USGS Version 3.0 Chesapeake Bay 1997 SPARROW (Brakebill and Preston, 2004 (B & P)) TN and TP models with the same catchments, but new compositional and configurational landscape metrics and a consideration of riparian stream buffers for non-point source and land-to-water delivery significance. New watershed-wide maps of LC/LU, % ISA, and % TC for 2000 were used. It was concluded that the new models improved the predictive ability of SPARROW and the precision of simulated annual TN and TP loadings reaching the estuary as compared with HSPF estimates, indicating that these two approaches may now be more complimentary.

Catchment-wide compositional landscape metrics of area-weighted mean urban (≥10% ISA) and non-agricultural non-urban patch sizes significantly depicted the generation of non-point N and P land sources eventually reaching the Chesapeake Bay. Whereas, compositional and configurational landscape metrics in catchments (percentage of extractive land, area-weighted mean edge contrast of deciduous forest, and percentage of cropland) that are thought to be associated with water quality at localized scales were shown here to be significantly correlated with the delivery of non-point N loadings to larger, nested river networks draining the estuary.

Additionally, at the localized scale, riparian stream buffers are thought to attenuate nutrients eventually reaching the stream channel. However, at the scale of the entire watershed, the demonstration here of the significant effects of LC/LU on TN and TP runoff extends to riparian stream buffer compositional percentages of evergreen forest and barren land increasing delivery of non-point N and P, respectively, to the entire Chesapeake Bay. Hence, these representations of LC/LU at catchment and riparian stream buffer width scales should be used in future data-driven water quality models representative of the entire Chesapeake Bay TN and TP watershed runoff. The increased transport of non-point N and P from all compositional and configurational land-to-water delivery landscape metrics to Chesapeake Bay streams at both catchment and riparian stream buffer-wide scales suggest the vital role that overland and shallow subsurface flow processes may play in enhanced nutrient transport as a result of decreased soil hydraulic conductivity linked to these and adjacent cover types.

In regards to the greatest reduction of non-point N transported to the Chesapeake Bay, future land management should be focused on reducing the highest percentages of extractive land in catchments located in central PA, western MD, and northeastern WV. Likewise, in terms of decreasing non-point P transported to streams draining the estuary, projected land management strategies should involve reducing percentages of barren land in riparian stream buffers within southeastern PA, central and the eastern shore of MD, southwestern DE, and central to southeastern VA. Thus, these and the rest of our findings are relevant to land managers, planners, lawmakers, and other stakeholders in making better-informed landscape decisions involving not only the overall nutrient health of Chesapeake Bay, but in similar watersheds elsewhere.

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